Strategic Directions for Hydrogen Delivery

Workshop Proceedings
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Sponsored by

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Office of Hydrogen, Fuel Cells, and Infrastructure Technologies Program

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Introduction

On May 7-8, 2003, more than 60 executives representing industrial gas companies, petroleum and natural gas companies, equipment suppliers, national laboratories and other research organizations, consulting/engineering firms, academia, and federal agencies met at the U.S. Department of Energy (DOE) Strategic Directions for Hydrogen Delivery Workshop. The Workshop was sponsored by the DOE, Office of Energy Efficiency and Renewable Energy, Office of the Hydrogen, Fuel Cells, and Infrastructure Technologies Program (OHFCIT). Participants met in small groups to discuss the key challenges and issues to be addressed in developing a safe, affordable national hydrogen delivery infrastructure, and the R&D and other activities needed to address these barriers. Four facilitated breakout groups were convened to address technology needs in different areas: Gaseous Hydrogen Delivery, Liquid Hydrogen Delivery, Solid and Liquid Hydrogen Carriers, and Bulk Hydrogen Storage. The results of the Workshop, summarized in this report, will be used to help structure the OHFCIT Program's hydrogen delivery R&D priorities and strategic directions. The report will also be provided to other interested federal stakeholders, including DOE's Office of Fossil Energy and the Basic Energy Sciences Program; the Department of Transportation; the National Science Foundation; and the Environmental Protection Agency.

Background

DOE Hydrogen Fuel Initiative

In his January 28, 2003, State of the Union address, President Bush expressed a goal of reversing America's growing dependence on foreign oil by developing commercially-viable hydrogen-powered fuel cells to power automobiles, homes, and businesses with no pollution or greenhouse gases. The President's new Hydrogen Fuel Initiative proposes to provide more than $1.2 billion in funding over the next five years to develop the technologies and infrastructure necessary to achieve this goal. By combining an accelerated R&D schedule on hydrogen fuel with the ongoing FreedomCAR Initiative, the President hopes to enable a commercialization decision on hydrogen-powered fuel cell technologies by the year 2015 -- about 15 years ahead of previous projections.

Government coordination of this huge undertaking will help resolve one of the difficulties associated with the development of a commercially viable hydrogen fuel cell vehicle....Which comes first, the vehicle or the infrastructure of manufacturing plants, distribution and storage networks, and convenient service stations needed to support it?...[The Department will work with all stakeholders] to develop both the vehicle and the infrastructure in parallel--and by so doing, advance a commercialization decision by 15 years, from 2030 to 2015.

— Energy Secretary Abraham
2004 DOE Budget Submission
February 3, 2003

The Challenge: Building a National Hydrogen Delivery Infrastructure

Hydrogen delivery -- the transportation of hydrogen from the point of production to the point of use (including handling and storing the hydrogen at refueling stations or stationary power facilities) -- is a major unsolved piece of the hydrogen infrastructure puzzle.

Current delivery systems must be significantly expanded in order to supply hydrogen to all regions of the country. Delivery systems will need to support both distributed and central hydrogen production facilities, since both types of production are likely to be used in an emerging hydrogen economy. Delivery by pipelines, gaseous truck, cryogenic liquid trucks and novel solid or liquid carriers are all options for hydrogen transport. Pipelines currently appear to be the best long term solution for delivering large quantities of hydrogen, but other cost-effective types of delivery systems will be needed as well. Special situations must be considered, such as delivery to remote or low-density population areas. Storage needs and costs within the delivery infrastructure must also be addressed.

The 2010 goal for the cost of delivered hydrogen — including production plus final delivery costs — is $1.50/kg (untaxed, at the pump). This means that the current cost of hydrogen delivery and off-board storage technologies must be significantly lowered. Recent estimates of the cost of long distance transport and handling of hydrogen from the point of production to the refueling unit range from $1.50 to $8.00/kg, depending on the distance and the method. The energy efficiency of delivery also needs to be improved. Current hydrogen compression and liquefaction technologies are too energy intensive.

OHFCIT Delivery Program Area

The Department of Energy's Office of Hydrogen, Fuel Cells and Infrastructure Technologies Program is launching a focused research and development (R&D) effort on hydrogen delivery, to begin with a set of competitively awarded R&D projects in fiscal year 2004.

The **goal** of the OHFCIT hydrogen delivery program area is to:

> ***Develop hydrogen fuel delivery technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power.***

The program will focus on meeting the objectives shown in the box by conducting collaborative R&D with industry, national laboratories and universities.

The following sections of this report summarize the proceedings of the Strategic Directions for Hydrogen Delivery Workshop, including the opening plenary session presentations, common themes, and detailed breakout group results.

OHFCIT Hydrogen Delivery Program Objectives

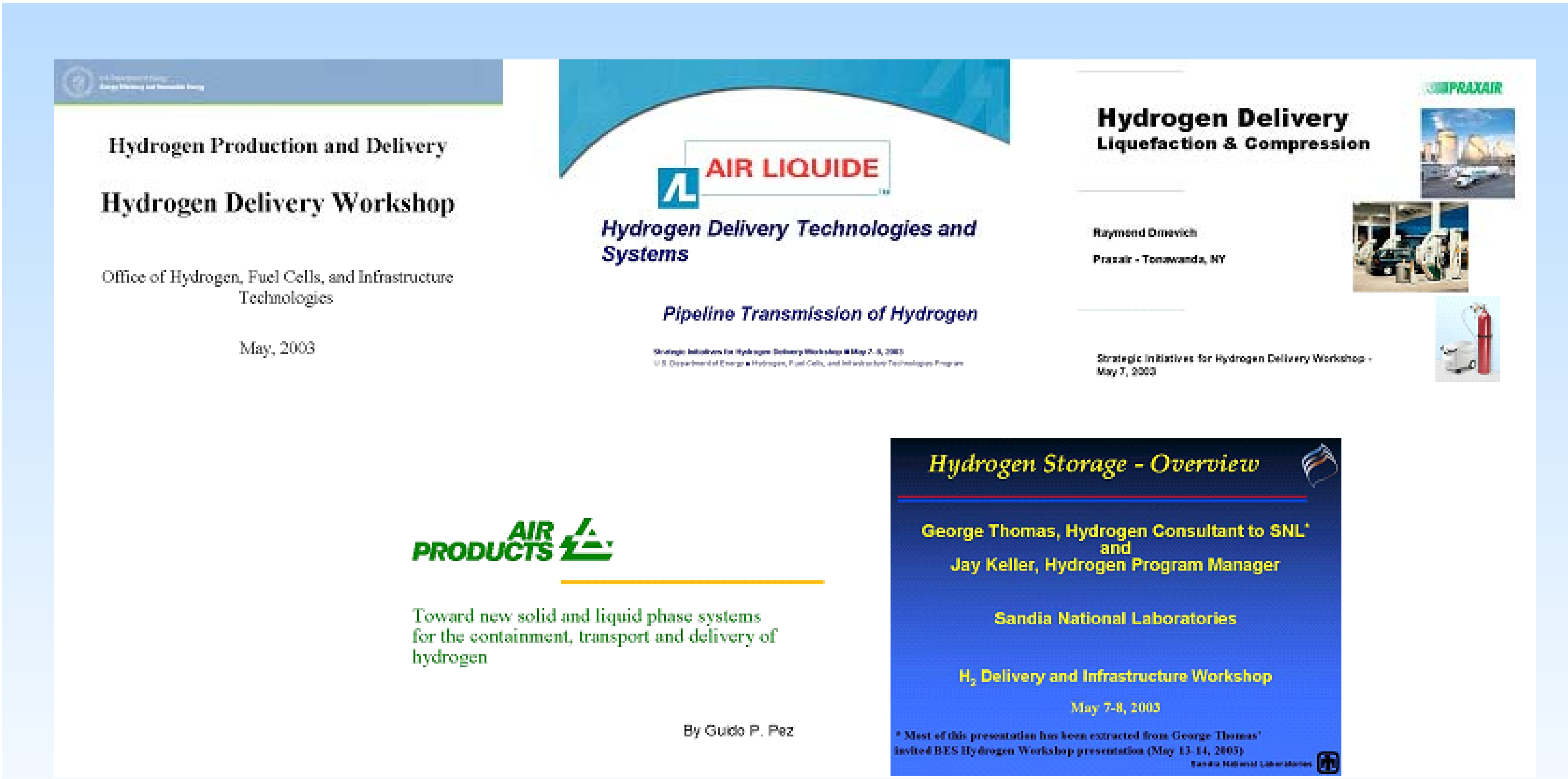
Understand Infrastructure Trade-offs and Options: by 2006, define a cost-effective and energy-efficient hydrogen fuel delivery infrastructure for the introduction and long-term use of hydrogen for transportation and stationary power.

Cost Reduction:

- *by 2010:* reduce the cost of hydrogen fuel *delivery from central/semi-central production facilities* to the gate of refueling stations and other end users to <$0.70/kg
- *by 2010:* reduce the cost of hydrogen *movement and handling within refueling stations and stationary power facilities* to an end-use device to <$0.60
- *by 2015:* reduce the *total cost of hydrogen fuel delivery* from the point of production to the end-use device to <$1.00/kg

Opening Plenary Presentations

As shown in the agenda in Appendix A, the meeting opened with an overview of the U.S. Department of Energy's Office of Hydrogen, Fuel Cells and Infrastructure Technologies Program. Four plenary presenters followed with summaries of the status of current and potential hydrogen delivery systems. The presentations, shown below, are provided as Appendix B.



Facilitated Breakout Session Results

Participants spent the bulk of the meeting in facilitated breakout sessions that focused on technology-based solutions to future market, technical, and regulatory challenges faced in developing a safe, affordable national hydrogen delivery infrastructure. Four breakout sessions were convened to address technology needs in the following areas:

- **Gaseous Hydrogen Delivery:** Development of new dedicated hydrogen pipelines; the possible use of existing natural gas pipelines for pure hydrogen or mixtures of hydrogen and natural gas; compression; reliability and safety; etc.
- **Liquid Hydrogen Delivery:** Development of large scale and small scale liquefaction technology, liquid transport issues, etc.
- **Solid and Liquid Hydrogen Carriers:** Development of more novel solid and liquid carriers such as hydrides, carbon nano-materials, hydrogen solvents, and other possible ideas.
- **Bulk Hydrogen Storage:** **B**ulk hydrogen and/or hydrogen/carrier storage needs within the delivery infrastructure at terminals, other surge capacity needs, as well as at the point of production and at the point of use at refueling stations and stationary power facilities.

Exhibit 1 provides a summary of the top-priority R&D needs for hydrogen delivery identified in each breakout group and Exhibit 2 shows the common themes that emerged during discussions. More detailed results are provided in the following sections and in Appendix C, which shows the summary presentations prepared by each breakout group for discussion during the closing plenary session. A complete list of the workshop participants is provided in Appendix D.

Exhibit 1. Summary of Top-Priority R&D Needs in Hydrogen Delivery

Gaseous Hydrogen Delivery	Liquid Hydrogen Delivery	Solid and Liquid Hydrogen Carriers	Bulk Hydrogen Storage
▪ Develop inexpensive new materials to allow hydrogen transmission in large-diameter, high-pressure pipelines without embrittlement, corrosion, leakage, etc. ▪ Develop in-line coating/lining materials for use in existing pipelines ▪ Develop safe, durable automated welding and/or innovative methods for joining pipes at low cost ▪ Develop and test effective hydrogen gas odorant that will not hurt fuel cell ▪ Develop innovative, low-cost leak detection (tracers, micromaterials, microsensors, etc.) ▪ Develop compressors with improved reliability and efficiency to minimize need for redundant systems ▪ Conduct membrane science R&D for improved hydrogen/natural gas separation ▪ Develop hydrogen infrastructure system models and studies to analyze different hydrogen production and distribution network options and scenarios, with the ultimate goal being a realistic, multi-energy, self-assembled distribution network model ▪ Develop codes and standards for handling hydrogen	▪ Conduct fundamental scientific research on innovative liquefaction technologies ▪ Investigate innovative liquid hydrogen storage concepts ▪ Investigate potential for improved ortho-para conversion technologies (to lower refrigeration requirements) ▪ Develop advanced alloys and manufacturing technologies for heat exchangers ▪ Develop integrated refrigeration and power generation systems ▪ Develop additives that could raise the liquefaction temperature and separate as liquid	▪ Conduct comparative systems analysis (point of production to point of consumption) of delivery system options and alternatives ▪ Conduct R&D to identify, discover, and utilize the optimum reversible liquid phase hydrogen carriers ▪ Conduct fundamental R&D on carbon nanostructures for storing hydrogen ▪ Develop methods/materials to increase the weight percent of metal hydrides and possibly optimize them for slurry delivery ▪ Use computational and analytical tools to evaluate hydrogen carriers (storage capacity and reaction heats) ▪ Investigate low cost, efficient, irreversible hydride regeneration coupled with hydrogen manufacture	▪ Develop manufacturing technologies for high pressure hydrogen storage vessels in large numbers of units and at low unit cost ▪ Develop inexpensive solid materials for low pressure hydrogen storage, recognizing that weight and footprint are not critical design parameters for bulk storage as they are for on-board storage ▪ Develop new materials for hydrogen containers that satisfactorily address hydrogen's unique leakage and embrittlement properties ▪ Develop low cost "smart" sensors for hydrogen detection, including further research on possible odorants ▪ Develop robust systems analysis and modeling capabilities for evaluating alternative scenarios and applications for bulk storage, with the first step being the creation of a simple spreadsheet analysis tool for analysis of appropriate RD&D targets for bulk hydrogen storage ▪ Conduct investigation of geologic storage technologies and models of the physical behavior of hydrogen in various types of underground geologic formations

EXHIBIT 2. COMMON THEMES

- ***Delivery Targets:*** Performance targets for delivery systems should clearly describe all assumptions, and should be based on thorough analysis that includes industry review. Generic delivery targets will not be particularly useful in measuring R&D progress for a particular technology, since the targets will vary greatly depending on the technology (e.g., bulk storage materials and containers require different targets; location, size, throughput, and maximum allowable pressure of a hydrogen pipeline will greatly affect cost; carrier-specific targets are needed for solid and liquid carriers).

- ***Need for Comparative Analysis of Infrastructure Options and Tradeoffs:*** Options and tradeoffs for hydrogen/carrier delivery from central and semi-central production to the point of use at refueling stations and other end uses for the introduction and long-term use of hydrogen are not well understood. Delivery options must be assessed in the context of a total system – i.e., the surrounding production, storage, and conversion infrastructure. Safety and risk of various options should be included as a part of the comparative analysis. Analysis is a critical near-term need for understanding the advantages and disadvantages of the various options, and for quickly eliminating dead ends and preventing false starts. Comparative systems models and analysis is important to guide research and investment efforts not only for the ultimate hydrogen delivery infrastructure, but also for the most appropriate infrastructure to be used during the transition period as hydrogen is introduced as a mainstay energy carrier.

- ***Need for Improved Materials of Construction:*** The use of hydrogen presents special material challenges in almost all aspects of the delivery system. Fundamental and applied research is needed to develop low-cost new and/or improved materials for building a hydrogen delivery infrastructure. Material needs include:
    - Materials that will not become embrittled when exposed to hydrogen
    - Materials that can transmit or store hydrogen for long periods of time without corroding or leaking hydrogen (under both high- and low-pressure conditions)
    - Materials that will resist wear and reliably perform in harsh operating conditions (e.g., in compressors, heat exchangers, cryogenic operating environments)

- ***Need for Hydrogen Leak Detection Technologies and Odorants:*** The ability to detect hydrogen leaks is essential from a public safety standpoint since hydrogen gas itself is odorless and burns with no visible flame. Attempts to odorize hydrogen gas have so far been unsuccessful since the hydrogen molecule is so much smaller than any odorant yet to be developed and escapes a system well ahead of the odorant. It is possible that public acceptance of hydrogen as an energy carrier will require odorization (or equivalent), so this should be a priority research activity. Leak detection technologies (e.g., smart sensors, microsensors, tracers, etc.) are also needed to monitor the delivery system status, and could be used as a substitute for odorization.

Gaseous Hydrogen Delivery Breakout Results

Hydrogen delivery by gas pipeline is currently the lowest cost delivery option at high volumes, and is likely to play a key role in distributing hydrogen in a future hydrogen economy. Few dedicated hydrogen pipelines exist—those that do are built to transmit hydrogen as a chemical feedstock for commercial use, and they are not adequate to broadly distribute hydrogen to serve hydrogen fuel cell vehicles. There are a number of technical barriers to gaseous hydrogen delivery, as shown in Table 1, below.

The characteristics of a future hydrogen pipeline infrastructure will depend on the hydrogen production infrastructure, the balance between central and distributed production facilities, and how pipelines compare to other delivery options. The size of the pipelines that are needed, the number and size of compressors that are needed, and a host of other factors will be affected by the nature of the overall production, storage, and delivery system.

Hydrogen pipelines will be required to distribute large volumes of hydrogen over long distances, which will require larger-diameter, higher-pressure pipelines. Metal embrittlement becomes a major problem at hydrogen pressures greater than 700psi, so development of low-cost materials that do not embrittle will be essential. Simpler, more reliable compressors will also be needed to reduce the cost of compression and reduce the need for redundant systems. During the transition phase, gas pipeline systems that can deliver a mixture of hydrogen and natural gas may play a role, which will require effective gas separation technologies. Safety concerns will require that cost-effective leak detection technologies (including an odorant, if possible) be developed and tested. Because construction and welding accounts for the majority of pipeline capital costs, technologies to automate or lower the cost of pipeline joining and welding in the field (which is currently a time- and labor-intensive manual effort) are needed. A summary of the top-priority R&D needs is provided in Exhibit 1; a more detailed list of RD&D needs for gaseous hydrogen delivery is provided in Tables 2 and 3.

Participants:
Gaseous Hydrogen Delivery

Name	Organization
Belinda Aber	ChevronTexaco
Mark Ackiewicz	TMS, Incorporated
Raymond Anderson	Idaho National Energy Engineering Laboratory
Greg Baehr	Praxair, Inc.
Jim Campbell*	Air Liquide Process & Construction
Steve Cohen	Teledyne Energy Systems
Maria Curry-Nkansah	BP
Rod Dyck	National Transportation Safety Board
Steve Folga	Argonne National Laboratory
Christopher Freitas	DOE/Office of Fossil Energy
David Greene	Oak Ridge National Laboratory
Michael Manning	Praxair, Inc.
James Merritt	DOT/Research & Special Programs Administration
Paul Scott	ISE Research
Allen Spivey	Gas Technology Institute
Steve Thomas	Sandia National Laboratories
Michele Touvelle	ExxonMobil

*** Session Chair and Presenter**

Facilitator: Shawna McQueen, Energetics, Incorporated

Gaseous Hydrogen Delivery
TABLE 1. TECHNICAL BARRIERS/PROBLEMS
□ = CRITICAL BARRIER

PIPELINE MAINTENANCE AND OPERATION	SYSTEM ISSUES	PIPELINE MATERIALS	PIPELINE CONSTRUCTION	PIPELINE SAFETY	COMPRESSION	INSTITUTIONAL BARRIERS (ECONOMIC, POLITICAL)
Lack of affordable, effective leak detection equipment □□□□□□□□ Lack of advanced real-time hydrogen metering technology □ Need for reliable, durable, cost-effective monitoring and diagnostic equipment Lack of cost-effective, better performing inspection technology □ – e.g., smart pig systems Do not fully understand impacts of hydrogen on meters, fittings, gaskets, etc. □ Do not understand effect of pressure cycling and directional changes on pipeline reliability □□ Do not fully understand pipeline metallurgy at operating pressures >700 PSIG – For existing pipelines – Embrittlement not issue <700 psig Need for better gas separation techniques □□□□□ – Hythane – Odorants	Do not understand how much storage will impact overall hydrogen cost targets Better understanding of non-technical issues around pipeline costs and ways to address Need better ways to accomplish distributed reforming □□□ Lack of cost effective small-scale hydrogen production units that could be in lieu of pipelines □□□ Need better metric/target definitions □ Lack of understanding of potential transport of hydrogen/ natural gas mixtures or multiple gas transport Need for a systems approach □□□□□□□□□	Lack of understanding of material science issues with respect to hydrogen gas embrittlement and enhanced fatigue cracking on pipelines □□□□□□□□□□ Lack of less costly hydrogen distribution piping materials □□ – Resistant to corrosion – Low permability – Problem: permeation of hydrogen through plastic pipelines Materials costs too high Unknown: best pipe quality (carbon content) for moving hydrogen	Lack of cost-effective (fast, reliable, inexpensive) new pipeline welding technology (fusion, auto, etc.) □□□□□□□□□ – Welding, joining, etc. costs are too high Lack of pipe liners that seal well and are cost-effective □ Lack of cost effective valve technology	Insufficient safety assurance procedures/ standards in place Lack of effective odorant for hydrogen distribution pipelines □□□□□□□□□ Lack of visible flame □□ Lack of experience operating pipelines at higher pressure □□ High concentration areas (HCAs) may not be defined appropriately for hydrogen pipelines □□	The need for multiple compressors (due to downtime problems) adds a lot to pipeline costs □□□□□□□□□□□ – Improve durability and reliability of compressors to minimize need for redundant systems Simpler mechanical compression mechanisms are needed	Lack of incentives to build infrastructure □□□□ Lack of public understanding of risks and benefits of hydrogen energy systems (public education)

Gaseous Hydrogen Delivery

TABLE 2. R&D NEEDED TO OVERCOME THE BARRIERS

ι = TOP PRIORITY, □ = HIGH PRIORITY, △ MEDIUM PRIORITY

PIPELINE MATERIALS ιι□	PIPELINE TECHNOLOGY □	ODORANTS AND LEAK DETECTION ιι	ADVANCED COMPRESSORS □□□□□□	HYDROGEN/ NATURAL GAS SEPARATION □	ECONOMIC/SYSTEMS STUDIES OR MODELS ιιιιιι	FIELD DEMONSTRATIONS	REGULATORY/ NON-TECHNICAL
Develop new materials (steels?) to allow high pressure transmission without embrittlement, etc. □□□□△△△△△△ Cheap, new material that allows for high pressure and does not embrittle, e.g., polyethylene □□□△△△△ – Plastics in general – Polymers (not steel) □□△△ Develop in-line coating/lining materials for use in existing pipelines □△△△△ Develop improved understanding of hydrogen embrittlement △△△△	Develop automated welding and/or innovative methods for joining pipes at low cost (lower cost, safe, durable, etc.) ιι□□△△△△ Develop/test non-mechanical metering technologies △△ Develop method for delivering multiple gases through co-axial pipelines □△△	Develop and test odorant that can be detected by most noses, is low cost, will stay entrained, and does not hurt fuel cell □□□△△△△△△△ – Correlated with hydrogen diffusivity Conduct research on flame visibility chemicals that do not poison fuel cells Conduct analysis to determine whether odorant is really required □△ – Micro-sensor alternatives? – Is there an odorant that will work with hydrogen? Develop innovative, low-cost technologies for detecting leaks in hydrogen pipelines □□□□□□□△△△△△△ – Tracers – Micromaterials – Microsensors – Cheap – Instead of odorant	Develop lower cost; more durable compression technologies/ techniques □□□□□△△△ Develop electrochemical hydrogen compressors △△△△△ Fund R&D partnership between compressor designers/ manufacturers and fuel suppliers Develop simpler compressors (e.g., guided rotor, linear compressors) Develop electrically driven membrane compressors	Conduct membrane science R&D □□□△△△△ Conduct adsorption science R&D	Conduct system analysis tradeoff study △△ – Supply/demand – System cost – System reliability Conduct analysis of the "must have" conditions for economic viability Analyses must consider how, where, and how much hydrogen will be produced relative to where consumed Regional study of exiting pipelines, including water or oil pipelines for hydrogen transport Assess viability of natural gas safety systems when hydrogen is introduced	Conduct field demonstration of hydrogen separation using existing natural gas pipeline infrastructure ι□△△ Fund demonstration facilities △ – In city with fleets – With odorant removal	Develop codes and standards for safe handling of hydrogen (fire) □△△△△△△△△

Gaseous Hydrogen Delivery
TABLE 3. ANALYSIS OF TOP PRIORITY R&D NEEDS

R&D NEED Identified as a top priority	**TECHNICAL ELEMENTS** Critical technical elements or milestones identified as a part of this R&D activity	**TIMEFRAME** Time from start of R&D to commercial application of results	**R&D IMPACTS** Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				**POTENTIAL PARTNERS** Potential partners for this R&D activity
			C	**S**	**R**	**E**	
Leak Detection and Odorants							
Leak Detection	Identify candidates suitable as tracers during hydrogen transport Identify candidates suitable as innovative leak detection technologies (e.g., microsensors, micromaterials, satellite imagery, aircraft mounted Develop innovative leak detection technologies and tracers Field demonstration of innovative leak detection technologies and tracers	3-8 years	2.5	4.5	4.4		• Instrumentation industry • Research labs/institutes (NIST, etc.) • National laboratories • Universities
Odorant	Identify candidates suitable for hydrogen leak detection Identify candidates suitable for hydrogen flame detection Compare candidates with respect to cost, human threshold, flow characteristics, and impact on fuel cell operation, and with respect to toxicity, flammability, and environmental impact Field demonstration of odorants for hydrogen transport	3-8 years	2.5	4.5	4.0		• Industrial gas companies • National laboratories • Universities • Research labs/institutes
Pipeline Materials							
Need for alternatives to steel such as advanced plastics and other polymers	Find or develop new/advanced polymers impermeable to hydrogen and test against a standard	3-5 years, new materials 3-5 years, standard development	4.5	4.0	4.8	2.0	• Government • Industry (federal gov't funding with industry cost share)

R&D NEED Identified as a top priority	**TECHNICAL ELEMENTS** Critical technical elements or milestones identified as a part of this R&D activity	**TIMEFRAME** Time from start of R&D to commercial application of results	**R&D IMPACTS** Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				**POTENTIAL PARTNERS** Potential partners for this R&D activity
			C	**S**	**R**	**E**	
Inexpensive, new material that allows for high pressure and does not embrittle	Develop alternative materials and test against a standard May need to develop new material standard for alternative pipeline material	>5 years	4.0	2.5	5.0	0.5	• National laboratories • Universities • Industry consort (federal gov't funding with industry cost share)
Develop in-line coating/lining materials for use in existing pipelines	Identify and test lining materials that improve operating integrity of existing pipe	3-5 years, product 0-3 years standard	4.5	4.0	4.8	2.0	• Industry • Government (federal gov't funding with industry cost share)
Develop new materials (steels?) to allow high pressure transmission without embrittle-ment, etc.	Greater than 24-inch diameter pipe Capable of handling gas at higher than 700 psig Test alloys for resistance to hydrogen embrittlement	0-3 years	4.0	4.6	2.0	0	• Industry • State/Federal regulatory agencies
Pipeline Technologies							
Develop automated welding and/or innovative methods for joining pipes at low cost (and safe, durable, etc.)	Survey present state of welding and fusion technology (e.g., electrical fusion and acoustic sensor/robotics) Select most viable approaches for R&D Design and test prototype	0-3 years	1.0	3.5	2.5	0.5	• Government labs • McDermot • Siapen • Existing manufacturers

R&D Need Identified as a top priority	**Technical Elements** Critical technical elements or milestones identified as a part of this R&D activity	**Timeframe** Time from start of R&D to commercial application of results	**R&D Impacts** Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				**Potential Partners** Potential partners for this R&D activity
			C	**S**	**R**	**E**	
Test existing non-mechanical metering	Test existing devices to ensure accuracy in transmission and distribution (orifice, ultra sound, vortex) — Follow NBS standards Publish results	0-3 years	2.5	0.5	3.6	0.1	• Gas producers • Daniel (gas meters producers) • Gas Research Institute (government agency)
Co-axial pipelines	Design, build and test prototype — 2-3 miles — Bury below ground — Pass 2 gases — Check for leaks at each end Demonstrate/manufacture co-axial pipeline	0-5 years	0.5	1.0	1.1	0.2	• Energy providers • National laboratories
Advanced Compression Technologies							
Need for compressors with improved reliability and efficiency	Higher efficiency electrical drives Reduce mechanical losses Improve volumetric efficiency Improved/reduced use of valves Simpler compressor design Minimize dynamic parts and seals Reduce exposure to contamination of hydrogen (i.e., from oil)	Linear compressors: 5-10 years Guided rotor compressors: 3-8 years Electrochemical compressors: 5-10 years	4.0 4.0 1.0	1.5 1.5 3.5	3.0 3.5 4.5	2.5 1.0 4.8	• Joint effort between industry, government, and equipment suppliers
Need for improved materials of construction	Develop materials to allow use of centrifugal compressors for high purity hydrogen compression Improve on hydride based compression Improve rider bands, piston rings, bearings and other wearing parts Improve cost of electrochemical compressor technology Eliminate use of expensive materials currently used in high pressure hydrogen compression	2-10 years	3.5	3.0	4.0	3.5	• Joint effort between industry, government, and equipment suppliers

R&D Need Identified as a top priority	**Technical Elements** Critical technical elements or milestones identified as a part of this R&D activity	**Timeframe** Time from start of R&D to commercial application of results	**R&D Impacts** Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				**Potential Partners** Potential partners for this R&D activity
			C	**S**	**R**	**E**	
Economic/System Studies or Models							
Need to develop realistic hydrogen infrastructure system models and studies to evaluate and compare different hydrogen production and distribution network options and scenarios	Develop economic device models to represent cost, conversion efficiency, energy/mass balance Develop energy demand/source scenarios to define future assumptions by geography and time Produce hand-selected distribution network scenarios (based on best judgments of modelers) Develop self-assembled distribution network models that provide automated strategy-scoping capabilities, optimized on economics, reliability, etc. (requires new computational science) Develop realistic, multi-energy, self-assembled distribution network models (add electric power, natural gas, etc.)	0-3 years 0-3 years 0-3 years 0-3 years 3-8 years	5.0	2.5	3.5		• Energy suppliers • Automotive manufacturers • National laboratories • Universities

Liquid Hydrogen Delivery Breakout Results

Hydrogen liquefaction is costly and energy intensive. However, liquid hydrogen delivery by truck or pipeline is likely to be a necessary part of the hydrogen delivery infrastructure, especially during the introduction period and in situations where lower volumes of hydrogen are needed. Key barriers include limitations to refrigeration technology, the high capital cost of liquefaction systems compared to the demand for liquid hydrogen, lack of technologies to manage/reduce boil-off, and lack of low-cost materials for low-temperature systems, as shown in Table 4

Dramatic improvements in technology will be required for liquefaction to meet the cost goals for delivered hydrogen. Fundamental research is needed to investigate innovative hydrogen liquefaction and liquid hydrogen storage technologies. Research is needed on two, parallel paths: 1) evolutionary improvements to existing liquefaction technologies in order to meet nearer-term needs for liquid hydrogen, and 2) investigation of potential breakthrough technologies that can lead to entirely new concepts and step-change improvements in liquid hydrogen technology. Research on advanced materials and additives and improved, integrated power and refrigeration systems are a few of the priority research needs for evolutionary technology improvements. A summary of the top-priority research needs is provided in Exhibit 1; Tables 5 and 6 show a more comprehensive set of R&D needs for liquid hydrogen delivery.

Participants:
Liquid Hydrogen Delivery

NAME	ORGANIZATION
Rodney Anderson	National Energy Technology Laboratory
Pete Devlin	U.S. DOE, OHFCIT
Ray Drnevich	Praxair, Inc.
Karl Jonietz	Los Alamos National Laboratory
Carl Landahl	Argonne National Laboratory
Stephen Lasher	TIAX
Michael McGowan	BOC Gases
Elizabeth Pfeiffer	BMW of North America
James Ragland	Aramco Services Company
Matthew Ringer	National Renewable Energy Laboratory
Prentiss Searles	American Petroleum Institute
Brad Smith	Shell Hydrogen

*** Session Chair and Presenter**

FACILITATOR: Keith Jamison, Incorporated

Liquid Hydrogen Delivery

TABLE 4. TECHNICAL BARRIERS/PROBLEMS

□ = CRITICAL BARRIER

LIQUEFACTION PROCESS TECHNOLOGY	LIQUID DELIVERY AND MANAGEMENT	SAFETY	MARKET	REGULATORY	POLICY	METROLOGY/ QUALITY ASSURANCE
Refrigeration technologies □□□□□□□ Liquefaction primary energy use reduction – bottoming, magnetic refrig. □□□□□ Expansion turbine efficiency and cost □□□□ Compression efficiency (and associated energy penalty) □□□ Low-cost heat exchange □□ Improved heat recovery □□ Ortho/para conversion efficiency Natural gas engine prime mover (fit to hydrogen compressors)	Boil-off management/ reduction □□□□□□□ – Storage tanks – Station – On-board – How to dispose High cost of materials for low temperature systems □□□□ Insulation efficiency of storage tanks Refueler to vehicle interface/commu nication Efficient and safe dispenses/ dispensing Delivery at required pressure	Safety issues detection of hydrogen leaks – public safety (cheap, reliable, etc.) □□□ Odorization □ – Liquid hydrogen – Gaseous hydrogen Flame visibility Lack low-cost seal analyzers	Lack distributed, alternative markets for hydrogen □□ Number of deliveries per station to match with assumed plant size – Market study	Codes and standards □□ – Siting – Dispensing – Safety – International harminization Slow diffuse codes and standards creation process especially fire and insurance □ – Differences in federal and state/local standards/ codes Data to support liquid hydrogen siting (codes and standards) and safety Lack standard specifications for a hydrogen commodity -will there be one? – Quality demand in application	Lack incentives to prime demand (e.g., hydrogen in (5-10%) natural gas) □□□□□	Lack low-cost impurity sensors □□ Metering liquid hydrogen – How to measure liquid flow

Liquid Hydrogen Delivery

Table 5. R&D Needed to Overcome the Barriers

ι = Top Priority, □ = High Priority, △ = Medium Priority

Liquid Delivery and Management	Liquefaction Process Technology	Safety	Regulatory	Market
Develop innovative liquid hydrogen storage concepts □□□□□△△△ Develop portable, low cost hydrogen reliquefier □□△△ – And/or for direct gas to liquid refueling at station Develop advanced cryogenic storage materials □□ – Withstand embrittlement – Improve seals/gaskets Gain better understanding of cryogenic insulators □□ Develop mobile vehicle boil-off containment/use devices □△△ Investigate higher pressure liquid delivery options □△△ Evaluate other uses for liquid hydrogen – refrigeration duel use △△△△ Develop efficient high pressure liquid hydrogen pumps for vehicle fueling △△△ Dewar (min. boil-off) storage tank design improvements □ Develop low cost advanced technology insulating materials △△ Investigate small liquid hydrogen trailer for multiple, small deliveries – (similar to milk runs) △△ Investigate dispensing nozzle improvement to make more economical △ Investigate low cost liquid hydrogen “drop-off” trailers (swappable)	Fund fundamental science on innovative liquefaction technologies, including novel compression technologies ιιιιιι□□□△ Develop new ortho-para conversion technologies □□□□□□ – Alternatives – At higher temperatures? Develop integrated refrigeration and power generation systems ι□△△△ Develop alloys for heat exchangers □△△△△ Develop additives that could raise the liquefaction temperature and separate as liquid ι△△△ Develop micro-channel heat exchangers for small-scale plants □△△△ Investigate mixed refrigerants □△ Investigate multimedia liquefaction nanotube/ liquid/gaseous methods △△△ Develop incremental compressor improvements Develop membrane or other separation device for improving hydrogen purification	Develop remote hydrogen leak detector □ Develop sold-state hydrogen sensors △△ Develop hydrogen odorants – Are they needed in vehicles? – Will odorant leak? Ensure tie-in with energy infrastructure/security	Conduct R&D to provide answers to code issues □□△ Develop dispensing technology incorporating weights and measures □△	Investigate new end-use applications for hydrogen (white paper studies) □△△ Investigate impact of 700 bar on existing market △ Investigate economic and technical feasibility of using hythane

Liquid Hydrogen Delivery

TABLE 6. ANALYSIS OF TOP PRIORITY R&D NEEDS

R&D Needs Identified as a top priority	**Technical Elements** Critical technical elements or milestones identified as a part of this R&D activity	**TimeFrame** Time from start of R&D to commercial application of results	**R&D Impacts** Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				**Potential Partners** Potential partners for this R&D activity
			C	**S**	**R**	**E**	
Develop additives that could raise the liquefaction temperature and separate as liquid	Solubilities Chemical issues Phase behavior End user impacts	7+ years	5	5	5		• Universities • National Laboratories • Chemical process industry • Specialty chemical manufacturers
Integrated refrigeration and power generation systems	Evaluate integration opportunities for small and large plants Investigate conventional integration and novel low grade waste	Modification of existing technologies = 4 years Novel tech = >7 years	2 4	2 4	2 4	2 4	• Universities • National Laboratories • Tech developers • R&D organizations • Industry gas companies
Develop alloys for heat exchangers (and manufacturing techniques)	Assess energy efficiency vs. cost → develop possible solution set Test new materials – develop engineered solutions	Go/no-go = 4 years Implement = 7+ years	2.5	N/A	1	5	• Universities • Industry • National laboratories
New orthopara conversion technologies	Assess energy efficiency properties Test catalysts for best temperature process Target LN_2 temperature	Go/no-go = 4 years Implement = 7+ years	5	NA	3	5	• National laboratories • Universities with industry assisting in problem definition
Innovative liquid hydrogen storage concepts	Materials Designs Load factors Logistics Peak shaving Codes, standards, regulations Systems approach	For codes, standards, and evolutionary improvements to existing technology: 3-7 years For new technology: 7+ years	3	3	3	3	• Tank manufacturers • Liquid hydrogen distributors

R&D Needs Identified as a top priority	**Technical Elements** Critical technical elements or milestones identified as a part of this R&D activity	**TimeFrame** Time from start of R&D to commercial application of results	**R&D Impacts** Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				**Potential Partners** Potential partners for this R&D activity
			C	**S**	**R**	**E**	
Fundamental science on innovative liquefaction technologies	Estimate refrigeration state of the art (cost, efficiency, other benefits and limitations) Investigate fundamental hydrogen properties/ interactions Evaluate non-conventional technologies	Modification of existing technologies = 4 years Novel technologies = >7 years	2 4	2 4	2 4	2 4	• Universities • National laboratories • Technology developers • R&D organizations • Industrial gas companies

Solid and Liquid Carriers Breakout Results

The use of solid or liquid hydrogen carriers that can release hydrogen without significant processing operations are possible transport/delivery options. As Table 7 shows, there are a variety of potential hydrogen carriers under investigation, all of which are in different stages of development. Current solid and liquid hydrogen transport technologies have high costs, and/or insufficient energy density, and/or poor hydrogen release and regeneration. The particular barriers facing the development of solid and liquid carriers are carrier-specific: Table 8 includes a list of some of the key technical barriers to the development of the main options being investigated today.

Current hydrogen carrier technologies require step change improvements to meet cost goals. Completely new concepts and technologies may also be discovered along fundamental research paths. In order to help focus R&D efforts, comparative systems analysis of all hydrogen delivery options and alternatives (from point of production to point of hydrogen consumption) are an essential near-term need. Top-priority R&D needs for carriers are summarized in Exhibit 1 and displayed in more detail in Tables 9 and 10 below. R&D needs are identified for a variety of carriers, including reversible liquid carriers, metal hydrides, irreversible (regenerable and non-regenerable) chemical carriers, nanotubes and other carbon structures, as well as for overall systems analysis and computational and analytical tools.

Participants:
Solid and Liquid Carriers

NAME	ORGANIZATION
John Anderson	TMS
Gene Berry	Lawrence Livermore National Lab
Stephen Chalupa	ChevronTexaco
Max Clausen	Pacific Northwest National Lab
Terry Copeland	Millennium Cell Inc.
Donald Hardesty	Sandia National Lab
J. Stephen Herring	Idaho National Energy/Eng. Lab
Theodore Motyka*	DOE/Savannah River
Guido Pez	Air Products & Chemicals
Gerry Runte	Gas Technology Institute
Edward Schmetz	U.S. Department of Energy
Richard Smith	National Science Foundation
Peter Teagan	Tiax
Brian Turk	RTI

*** Session Chair and Presenter**

FACILITATOR: Ross Brindle, Energetics, Incorporated

TABLE 7. EXAMPLE SOLID AND LIQUID CARRIERS

EXAMPLE CARRIERS	TWO-WAY PROCESS	STAGE OF DEVELOPMENT
Methanol/ethanol	No	3
Ammonia	No	3
Reversible liquids (decalin/naphthalene)	Yes	2+
Fischer-Tropsch liquids	No	2+
Glass microspheres	Yes	1+
Carbon Nanotubes	Yes	1
Hydride solids (chemical)	Yes	2
Hydride solution chemical	Yes	2
Hydride solid (metal, reversible)	Yes	2+
Hydride slurry	Yes	1

Two-Way Process indicates a return stream for hydrogen carriers is required with this carrier system

Stage of Development:

1 = R&D stage

2 = Demonstration, scale-up, early development stage

3 = Commercial stage (still requires development)

Solid and Liquid Carriers

Table 8. Technical Barriers (1 of 2)

□ = Critical Barrier

Overarching Barriers	2-Way System Barriers	Reversible Metal Hydride Solids	Hydride Slurry □	Irreversible Hydrides and Hydride Solutions □
Lack of comprehensive systems analysis for comparison of carrier options and alternatives □□□□□□□□ Safety in vehicle accidents □□□□ Rate of charge or discharge of carrier □□□ Hydrogen carrier materials must require comparable or lower energy than the hydrogen they transport on lifecycle basis □□□ Carbon-containing liquid carriers must be better carriers than fuels □ Hydrogen carriers must be superior to liquid hydrogen □ Hydrogen absorbents under pressure must store more hydrogen than the volume of gas they displace Low volumetric hydrogen content per unit of carrier Potential high cost of carriers compared to liquid fuel transport By-products released to environment could be potential barriers Uncertainty regarding R&D expense required for carriers early in development (e.g., nanotubes, hydride slurries) - left to marketplace?	Long-term (multi-cycle) purity of carrier agents (build-up of contaminants) Added handling and infrastructure costs for return streams	High weight per kg hydrogen □□□□□ Limited understand of the physical and chemical kinetics and role of dopants/ catalysts in metal hydrides □□ High cost of metal hydrides □ Metal hydrides must use only abundant, cheap raw materials (e.g., not lithium) Energy penalty for life-cycle hydrogen delivery using metal hydrides Possible safety (dispersal, pyrophoricity) and/or life cycle issues associated with metal hydrides <u>Key Strengths</u> High volumetric storage capacity They are known, relatively safe, and possibly energy efficient	Possible safety barriers (chemistry dependent) High cost and weight R&D costs for developing new materials <u>Key Strengths</u> Slurries could be piped using existing infrastructure Possible safety benefits	Regeneration processes and efficiency for chemical hydride solids and solutions □□□□ <u>Key Strengths</u> High storage capacity Easy generation of hydrogen

Solid and Liquid Carriers

TABLE 8. TECHNICAL BARRIERS (2 OF 2)

□ = CRITICAL BARRIER

METHANOL, ETHANOL, ETC. □□	FISCHER-TROPSCH LIQUIDS □□	AMMONIA □	REVERSIBLE CHEMICAL LIQUID HYDROGEN CARRIERS (E.G., DECALIN) □□□□	CARBON NANOTUBES □□	GLASS MICROSPHERES
Toxicity Water affinity Greenhouse gas emissions Currently based on fossil fuels Cost considerations Carbon-based systems have separation and purity issues Carbon-based systems have energy requirements for both formation and conversion Equipment to extract hydrogen is complex Key Strengths Well-understood and prevalent material High hydrogen content	Lack of understanding of which F-T liquids make the best hydrogen carriers □□□□ Carbon-based systems have energy requirements for both formation and conversion Carbon-based systems have separation and purity issues Equipment to extract hydrogen is complex Carbon sequestration at end use Key Strengths Easily transported liquid material using today's infrastructure No water affinity High hydrogen content	High (>300°C) decomposition temperature Safety Odor Toxicity 90% of NH_3 comes from natural gas and 30% is imported Materials issues for larger scale use due to caustic nature of NH_3 Key Strength Carbonless hydrogen carrier	Decomposition temperature of decalin to hydrogen is too high (300°C) □□□□ Key Strength □□ High hydrogen carrying capacity with no carbon emission problems Safe Can use existing infrastructure	Novel approaches like carbon nanotubes require extensive R&D □□□□□ – Continued nanotube research – Novel solid carriers – Transition from lab to bulk mfg Hydrogen interaction energy △H needs to be increased from 4 to 6-8 kcal/mole □□ Hydrogen density in carbon nanotubes is not fully understood □ Manufacturing cost and energy required Key Strengths Potential for lightweight adsorbent Purely physical process	Low hydrogen interaction energy (△H) Requires a two-way system with return streams Low energy density (losses) Key Strength Safety

Solid and Liquid Carriers

Table 9. R&D Needed to Overcome the Barriers

ι = Top Priority, □ = High Priority, △ Medium Priority

Analysis	Reversible Liquid Carriers	Reversible Hydrides	Computational and Analytical Tools	Irreversible Regeneration	Nanotubes and Other Carbon Structures	Irreversible, Non-Regenerable Carriers
Conduct comprehensive benchmarking comparison analysis ιιι□□□□△△△△△△ — Life cycle energy, cost, and safety from point of production to point of consumption — Develop systems analysis tools for scenario, risk, and pathway comparison of alternative delivery systems and components including technology, safety, economics, and policy Conduct system engineering of integrated delivery with production, storage, and delivery ι□□□□△△△△△ — Integrate delivery with closing the carbon cycle — Define and minimize the integrated cycle energy cost throughout entire hydrogen pathway Perform an analysis on the benefit, cost, safety, etc. of slurry vs. solid hydride △△△△△△ (6)	Identify, discover, and utilize the optimum reversible liquid-phase a hydrogen carriers ιιι□□□△△ — "Liquid hydrides" — Low-△H — Organic Relative evaluation of liquid carriers versus other delivery methods □□□△△△△△△ — Investigate efficiency of liquid hydrogen carrier options	Increase weight percentage of hydrogen on hydrides and hydride slurries □□□□□△△△△△ Research on improved charge and discharge kinetics □□△△△	Use computational and analytical tools to evaluate introduction of liquid hydrogen carriers □□□□△△△△△△ Develop reliable methods to measure hydrogen storage capacities and reaction heats of new carrier options (e.g., nanotubes, microspheres) □△△ — Reliable laboratory capacity measures — Production scale-up issues	Couple irreversible hydride regeneration with hydrogen production ιι△ Investigate new low-cost, regenerable chemical processes □□□ Conduct basic research on efficient irreversible hydride regeneration △△△	Conduct fundamental research on carbon nanostructures (including single wall nanotubes) for storing hydrogen □□□□□□□△△ — Consider new materials synthesis, characterization hydrogen adsorption measurements and guiding computational chemistry — Modeling to determine and verify if any carbon structures achieve storage densities of practical interest — Single-wall carbon nanotubes with a higher affinity for hydrogen	Study optimal Fischer-Tropsch liquids for hydrogen genera-tion at dis-tributed generation sites ι□△ Demonstrate and confirm that existing petroleum pipeline systems can be used in methanol and ethanol service △△

Analysis	Reversible Liquid Carriers	Reversible Hydrides	Computational and Analytical Tools	Irreversible Regeneration	Nanotubes and Other Carbon Structures	Irreversible, Non-Regenerable Carriers
Relative economic study of "ideal" reversible liquid hydrogen carrier □△△△△△△△△△△ Evaluate small scale on-site reforming of something other than methane □△ – Technical issues – Cost						

Solid and Liquid Carriers

TABLE 10. ANALYSIS OF TOP-PRIORITY R&D NEEDS

R&D PRIORITIES Identified as a top priority	TECHNICAL ELEMENTS Critical technical elements or milestones identified as a part of this R&D activity	TIMEFRAME AND MILESTONES Time from start of R&D to commercial application of results	R&D IMPACTS	R&D IMPACTS Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				POTENTIAL PARTNERS Potential partners for this R&D activity
				C	S	R	E	

Investigate low-cost, efficient irreversible hydride regeneration coupled with hydrogen manufacture	Using $NaBO_2 \rightarrow NaBH_4$ as a model, though that particular hydride may not be final choice
	Regeneration reaction is the missing link
	Potential routes:
	– Thermochemical
	– Electrochemical
	  – High-T (600C)
	  – Low-T (50-250C)
	– Multi-step
	  – Concentrate on most difficult step
		2004-06: Basic research on reactions
		2005-07: Bench-scale process development
		2006-08: Pilot plant
			Cost
			– Reduce by 10-100x
			Safety
			– Liquid, room temperature, atmospheric carrier, low flammability
			Reliability
			– Simple gen-system, low capital cost, on-board
			Energy Efficiency
			– 3x reduction in energy input meets 2010 hydrogen density goals (10%)
				2.8	4.8	3.5	2.3	• Borax suppliers
								• Current hydrogen suppliers
								• Industrial chemical companies with similar electrochemical capabilities
								• Auto companies
								• Fuel cell manufacturers
								• Traditional suppliers of hydride for other purposes

Conduct R&D towards the identification discovery and utilization of the optimum reversible liquid hydrogen carriers	Effective liquid phase hydrogen delivery at moderate/low pressure and temperature with potential to use current infrastructure and technology Material election/screening – Reaction energy for hydrogen addition removal – Kinetics – Catalysis – Energy density – Practicality – Safety – Disposal/benign – Temperature/press – Stability – Cost	Current: Decalin $\rightarrow$ Naphthelene 2005: Identify 5-10 serious potential candidates 2010: multiple candidates enter pilot-scale demo		3.5	4.5	2.0	4.5	• Universities • National laboratories • Industry (energy/ chem.) • Research institutes

R&D PRIORITIES Identified as a top priority	TECHNICAL ELEMENTS Critical technical elements or milestones identified as a part of this R&D activity	TIMEFRAME AND MILESTONES Time from start of R&D to commercial application of results	R&D IMPACTS	R&D IMPACTS Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				POTENTIAL PARTNERS Potential partners for this R&D activity
				C	S	R	E	
Conduct benchmarking comparison study of delivery methods and impact on overall system integration Selection of novel hydrogen delivery systems and their cost and efficiency goals should be based on their impact on the entire hydrogen system in comparison to benchmark or alternative systems	Analysis must be on point of production to point of consumption basis Use systems analysis and engineering to focus on impacts of delivery element on overall system performance Safety – Risk assessment → risk ranking → prioritization of risks Life Cycle – Include both energy efficiency and total costs and emissions (waste recycle)	2003: Begin benchmarking study early 2004: Identify high-level issues and compile draft document late 2004: peer review draft, revise 2005: publish study	Safety – Prioritize some technical work – Begin developing mitigation – Develop education outreach Cost – Focus on short term safe and practical – understand long term issues Reliability – Focus on transition option issues system wide Energy Efficiency – Relates to cost and emission	2.5	4	1	2	• National laboratories • Industry • Universities
Conduct R&D to increase wt% of metal hydrides and possibly optimize them for slurry delivery	Continue ongoing development of complex hydrides as onboard storage materials Perform a preliminary technical and economic analysis to determine feasibility and advantages of applying these materials to slurry/solution delivery Perform bench-scale tests to demonstrate proof of concept and then to optimize material performance Perform pilot-scale engineering demonstration as hydrogen delivery system	2004: go/no-go on preliminary analysis 2003: Bench-scale verification 2011: Pilot-scale validation		3	5	3	4	• National laboratories • Universities • Research institutes • Industry

R&D PRIORITIES Identified as a top priority	TECHNICAL ELEMENTS Critical technical elements or milestones identified as a part of this R&D activity	TIMEFRAME AND MILESTONES Time from start of R&D to commercial application of results	R&D IMPACTS	R&D IMPACTS Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				POTENTIAL PARTNERS Potential partners for this R&D activity
				C	S	R	E	
Use computational and analytical tools to evaluate hydrogen carriers (storage, capacity and reaction heats)	Provide the computational and analytical tools that will guide the research toward finding the needed solid and liquid hydrogen carriers and experimentally determine the critical properties for their effective use	10/2005: Develop quantum mechanics based computational methods for modeling weak (< 10 kcal/mol) van der Waals-type interaction energies. Particularly for predicting the hydrogen adsorption energies on practical hydrogen storage materials and carbon nanostructure, nanotubes, etc. 10/2005: Develop reliable methods for measuring the critical physical properties for hydrogen storage for solid and liquid carriers. Includes measurement of hydrogen isotherms, reaction heats and kinetics 10/2006: Complete computational models for reversible liquid and solid hydrogen carriers (e.g., decalin to naphthalene systems, carbon nanotubes hydrogen sorbents, etc.) 10/2006: Establish models for defining research protocol for developing preferred solid and liquid carriers	The computational guidance on the necessary analytical methods will lead to a more efficient, less costly R&D process for hydrogen delivery					

R&D Priorities Identified as a top priority	Technical Elements Critical technical elements or milestones identified as a part of this R&D activity	Timeframe and Milestones Time from start of R&D to commercial application of results	R&D Impacts	R&D Impacts Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				Potential Partners Potential partners for this R&D activity
				C	S	R	E	
Conduct fundamental R&D on carbon nanostructures for storing hydrogen including material synthesis, characterization, hydrogen adsorption measurement, and verification	Ability to synthesize carbon nanostructures of a desired configuration using computational science methods Provide a theoretical, underpinning for carbon nanostructures – hydrogen interaction Conduct definitive experiments to measure the fundamental hydrogen interaction properties of the nanostructures Production techniques for viable qualities of promising materials Prototype testing for integration into a delivery system	2003 – 2010: Basic research agenda, synthesis, computational science, and hydrogen-sorption measurement work 2005 – 2010: Nanostructure production methods in quantities needed for engineering testing	Extremely safe and reliable – solid state Cost is uncertain in the long run Efficiency potentially high because of reversibility	3.5	5	4.5	4	• Universities • National laboratories • Involve gas companies at an early stage

Bulk Hydrogen Storage Breakout Results

Bulk storage of hydrogen is a key element of the delivery infrastructure for the hydrogen economy. Like natural gas, bulk hydrogen storage can be accomplished in large tanks or in geologic formations. As such, the footprint and weight requirements are much less restrictive for bulk storage than for on-board vehicle storage. Similar to natural gas, it is expected that low cost bulk storage will be needed for efficient system operations to address daily and seasonal swings in supply and demand. The requirements for bulk hydrogen storage systems generally fall into three broad size classes:

- <50 ("tens of") tons for on-site storage at fueling stations or distributed generation facilities
- 50-1000 ("hundreds of") tons for storage at terminals or depots, probably located outside of major centers of hydrogen demand
- >1000 ("thousands of") tons for storage on-site at major hydrogen production facilities or in other locations between the production facilities and hydrogen storage terminals or depots

Participants: Bulk Hydrogen Storage

NAME	ORGANIZATION
Ron Chittim	American Petroleum Institute
Anthony Cugini	National Energy Technology Laboratory
Charles Forsberg	Oak Ridge National Laboratory
Jay Keller	Sandia National Laboratories
Marty Krongold	Air Liquide America, L.P.
Marianne Mintz	Argonne National Laboratory
George Parks	ConocoPhillips
Venki Ramen*	Air Products & Chemicals
Lixin You	ChevronTexaco
Bill Liss	Gas Technology Institute
John Petrovick	Los Alamos National Laboratory
Scott Savage	Air Liquide America, L.P.
Marvin Singer	DOE/Fossil Energy
Moe Khaneel	Pacific Northwest National Laboratory

*** Session Chair and Presenter**

FACILITATOR: Rich Scheer, Incorporated

However, there is much uncertainty about the specific requirements for bulk hydrogen storage systems. Much depends on how the infrastructure for the overall hydrogen economy evolves, including preferred modes of hydrogen production, transport, and end-use applications. As a result, at this early stage of hydrogen energy development, it is important to avoid rushing to "rule out" options prematurely. Multiple pathways for bulk hydrogen storage need to be considered.

Despite the uncertainties, one thing is clear: for bulk hydrogen storage to play a significant role in the hydrogen economy, the costs of doing it need to be extremely low. In the end, the costs probably need to be at least comparable to the costs of bulk storage of natural gas today. A comprehensive list of barriers to bulk hydrogen storage is shown in Table 11.

Finding ways to lower the costs of bulk hydrogen storage is one of the most important barriers to address. It is difficult to determine which bulk storage concepts to focus on for cost reduction because there is a lack of models and analysis tools for evaluating hydrogen infrastructure alternatives and pathways. For example, the technologies and techniques for lowering costs of hydrogen storage in underground caverns are far different than those for high-pressure or low-pressure tanks or vessels. Robust analysis is needed to determine the performance requirements of the bulk hydrogen storage systems under a variety of scenarios and end-use applications.

Bulk Hydrogen Storage

TABLE 11. TECHNICAL BARRIERS/PROBLEMS

□ = CRITICAL BARRIER

BULK STORAGE ECONOMICS	PERFORMANCE ISSUES OF BULK HYDROGEN STORAGE	MARKET AND INSTITUTIONAL ISSUES	STORAGE DEVICES AND TECHNOLOGIES	INFRASTRUCTURE DEFINITION – PROBLEM DEFINITION
High costs of bulk storage □□□□ – Cost/viability of cavern storage? – High compression costs – Improving costs with cushion gases	Maximum pressure storage temperature, pressure, and dischargeability □ Knowledge of hydrogen behavior in different geologic formations □□□□□□ Knowledge of behavior of hydrogen in underground containers Storage leakage control (containment) □ Leak detection □□□□□□□□□ – Odorants – Sensors Durability of storage technology □ Evaporation loss for liquid hydrogen	Lack of space at filling stations -- need acceptable footprint □□ Lack of codes and standards to enable hydrogen use at filling station and on-site generation – include safety protocols □□□□□□□□ – Proximity to people at filling station – Compatibility of hydrogen and other fuels – how it affects footprint and storage requirements Current marketing system for gasoline, e.g., multiple stations at a single intersection Lack of user-friendly technologies (no experts self service) □ Health and environmental impacts of various storage technologies Lack of operations/ maintenance support infrastructure Independent fuel suppliers jobbers	Lack of solid phase bulk storage (50-1000 psig) that are "robust" and can be cycled – Cheap low temperature MH alloys Lack of cost-effective new materials for preventing leakage and embrittlement □□ Storage material compatibility with hydrogen – Pressure – static and dynamic □ Lack of low cost compression technology □□ Heat management for storage □□□□ – Liquid – Solid – Gas	Lack of assessment of compatibility of hydrogen storage to current gas storage costs □□ Problems with storage – vehicle interface Lack of knowledge of cost tradeoffs between more storage vs. capacity factor of market production □ Lack of system optimization analysis □□□□□□□□□□□□□ – Lack of a model to provide cost target; how much cost is available for storage in total delivered hydrogen cost?

One of the potential low cost methods is bulk storage of hydrogen in geologic formations. This is a common form of storage for natural gas, and is being considered as a method for the sequestration of carbon dioxide. However, there is little geologic information on the physical attributes of underground formations for low cost hydrogen storage. Hydrogen has different properties than natural gas and these considerations need to be taken into account.

Another potential method is the use of solid-phase materials for low-pressure bulk storage. Such materials are being researched for on-board storage of hydrogen. It is not clear that the capital and life cycle costs of these materials can be made low enough for practical application in the bulk storage of hydrogen, and long-term durability and reliability are key unresolved issues. Further work needs to be done to develop solid-state materials for bulk hydrogen storage and new methods for manufacturing them on a large scale.

Public concerns about the safety of hydrogen storage need to be addressed. Low cost hydrogen sensors need to be developed. Further work needs to be done to develop odorants for hydrogen gas streams. The top-priority research needs for bulk hydrogen storage are presented in Exhibit 1. A more detailed listing of the research, development, and demonstration needs for bulk hydrogen storage is shown in Tables 12 and 13.

Bulk Hydrogen Storage

TABLE 12. R&D NEEDED TO OVERCOME THE BARRIERS

ι = TOP PRIORITY, □ = HIGH PRIORITY, △ MEDIUM PRIORITY

ADVANCED CONCEPTS	ADVANCED MATERIALS	DEMONSTRATION AND TESTING	TOOLS AND TECHNIQUES	CODES AND STANDARDS	STUDIES AND ANALYSIS
Modular hydrogen storage concepts (plug & play) △ Develop underground (geologic) storage technology for hydrogen ι□□□△△△△△ — Develop low-cost sealant for hydrogen cavern storage — Adsorption in existing formations Develop manufacturing technology for high pressure tanks in large volume, low cost ιιιι□□□△ Develop low cost/high pressure/small pipelines □△△△ "Hybrid Storage" □△△ — High pressure cryo — Low temperature-high SA solids Develop improved/lower cost compression technology □□△△△△ Rapid hydrogen loading and unloading on solid state storage □□△△△△ — Thermal management and optimization of charge and discharge Faster kinetics for solid-state hydrogen storage	Search for cheap solid materials for low pressure storage ι□□□□△△△ — Phase change materials for thermal management — Effects of hydrogen impurities on storage Development of new materials with good no leak and embrittlement properties ιι□□□□□△△△ — Study long term hydrogen materials interaction — Storage tank material degradation by hydrogen (embrittlement) — Characterization of permeation and structural properties of materials — Steel for low cost — Large scale composites	Demonstration of underground storage at urban hydrogen fueling stations/address standards △△ Facility for prototype and component testing △△△△△ Determine a "critical mass" of users necessary to support a pilot "micro" hydrogen economy	Develop smart sensors systems to use in leak detection □□□□□□□△△△ — Embedded — Low cost — Reliable — Rapid response — Safety — Odorants for hydrogen Fund a robust systems analysis program to help define the R&D infrastructural landscape ι□□□□△△△△ — Develop an economic model to optimize cost of production and storage — Develop a model of complex system economics and evolution (production – delivery – storage and dispensing) — Develop an easy-to-use techno-economic models for screening options (spreadsheet level) Dispensing technology for different bulk storage (gas, liquid, solid carrier) △△△△△△ — Easy to use — Convenient — User-friendly — Robotics for hydrogen dispensing/delivery	Fund a robust program in developing building, fire, and safety codes and standards for hydrogen infrastructure for generic public ιι□□△△△ — Re-visit footprint requirement for joint product dispensing and storage — DOE-led effort to remove/lower barriers to hydrogen storage — DOE coordinate codes and standards activities	Study footprints required for filing stations and distributed generation facilities △ Study to investigate compatibility/viability of current available storage options □△△△△ — Robust study regarding current storage technology leak rate detection and issues Economic analysis for different storage methods □□□△△ — Study of current capital costs for storage — Scenario analysis to define hydrogen bulk storage needs Test model behavior of hydrogen in various geologic formations suitable for storage ι□□□△△ — Study the design, construction and economics of hydrogen dome storage Life cycle and system analysis △△△△△△△ — Full-scale "Energy/Exergy" study of storage options

Bulk Hydrogen Storage

Table 13. Analysis of Top Priority RD&D Needs

RD&D Need Identified as a top priority	**Technical Elements** Critical technical elements or milestones identified as a part of this R&D activity	**Timeframe** Time from start of R&D to commercial application of results	**R&D Impacts** Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				**Potential Partners** Potential partners for this R&D activity
			C	**S**	**R**	**E**	
Create a robust systems analysis and modeling program to define the R&D infrastructure and scale	Continuous dependence on boundary constraints Infrastructure description "Evergreen" stakeholder-driven process Data collection via above Overall effort addresses hydrogen production, storage, delivery, purification and dispensing modeling User-friendly techno-economic model process results	Initial version – near-term Continuous updating based on changing boundary conditions	3	4	5		• Universities • Industry • National laboratories • Utilities • City industry
Develop smart sensors to use for leak detection	Develop rapid detection capability of hydrogen in ambient conditions at TBD concentrations Develop self-calibrating and self-validating sensors Cheap sensors based on "smoke" or "CO" detector concept Develop viable odorant/dopant to enhance detectability Embedded or in-place sensors/systems capable of detecting system integrity and appropriate response	RD&D requirements would demand near-term	0	0.5	4	5	• Instrumention companies with experience • National laboratories • Universities
Develop new materials with good, no leak, and embrittlement properties	Characterize permeation and structural behavior of existing materials (currently used in hydrogen storage) in the presence of hydrogen Use techniques like combinatorial chemistry to design alloys and composites with desired properties and low cost Study long-term hydrogen interaction with materials (now and existing materials – potential degradation) Develop welding (solid-state) and sealing techniques to eliminate leaks	Mid-term	4	5			• National laboratories, including nanoscience centers • Industry • Universities • Alloy makers • Composite makers

RD&D NEED Identified as a top priority	**TECHNICAL ELEMENTS** Critical technical elements or milestones identified as a part of this R&D activity	**TIMEFRAME** Time from start of R&D to commercial application of results	**R&D Impacts** Impacts (0-5 scale) of this R&D on hydrogen delivery Cost (C), Safety (S), Reliability (R), Energy Efficiency (E)				**POTENTIAL PARTNERS** Potential partners for this R&D activity
			C	**S**	**R**	**E**	
Develop manufacturing technologies for high pressure tanks in large volumes and low cost	Review current technology and identify/develop better alternatives Develop optimal trade-offs (size, material, fabrication, technology) for standard products Develop uniform standards of materials and fabrication	Alternative tech – Mid Trade-offs and standards – Near	0.3	0.5	1.5	4	• Materials manufacturers • Industry gas manufacturers • Vessel fabricators • ASME • DOT • Universities (manufacturing centers of excellence)
Search for cheap solid materials for low pressure storage (weight not critical)	Screening for low cost materials System analysis, thermal integration, scale/sizing Operational and life validation	3-10 years Small-scale: 3-4 years Large-scale: 5-7 years New materials: 5-7 years	1	2	4	5	• Universities • Material suppliers • Energy companies • National laboratories
Develop geologic storage technologies and model hydrogen in various geologic formations	Survey H_2/He storage (<3 year) experience Evaluate other geologies (permeabilities/cycle rates) (<3 years) Define areas of country with viable sites (<3 years) Can we develop technology to prevent leaks (>10 years) Impurity control on retrieval hydrogen Chemical reaction geology/hydrogen (3-10 years)	Regionally dependent Key cost factor – Cheap storage in a few parts of the country/expensive elsewhere – Technology development to get low cost across the country – Geology variable					• USGS • Gas Institute/ INGAA/CGA • Universities • National laboratories

APPENDIX A
Strategic Directions for Hydrogen Delivery Workshop -- AGENDA

DAY ONE – May 7, 2003	
8:00 am	Overview of the Hydrogen, Fuel Cells, and Infrastructure Technologies' Hydrogen Production and Delivery Program ▪ Mark Paster, U.S. DOE, Hydrogen, Fuel Cells, and Infrastructure Technologies Program
8:30 am	Plenary Presentations: Status of Hydrogen Delivery Technologies and Systems ▪ Pipelines, Jim Campbell, Air Liquide America L.P. ▪ Compression and Liquefaction, Ray Dnrevich, Praxair, Inc. ▪ Solid and Liquid Carriers, Guido Pez, Air Products and Chemicals, Inc. ▪ Storage (in delivery system), Jay Keller, Sandia National Lab
10:10 am	Breakout Instructions and Process Overview, Shawna McQueen, Energetics
10:35 am	Four Facilitated Breakout Sessions – organized by technical topic areas: ▪ Gaseous Hydrogen Delivery ▪ Liquid Hydrogen Delivery ▪ Solid and Liquid Carriers ▪ Hydrogen Storage Solutions
12:00 pm	LUNCH
1:00 pm	Breakouts resume – outcomes from breakout sessions will include ▪ Goals and refined technical targets ▪ Technical challenges/barriers to achieving the goals/targets ▪ Prioritized set of research and other activities
5:00 pm	ADJOURN
DAY 2 – May 8, 2003	
8:30 am	Breakout Groups meet to review output and develop reports (Powerpoint presentations) for Plenary group
9:30 am	Breakout Groups report results to the Plenary group
11:15 am	General Discussion, Closing Remarks and Next Steps
12:00 pm	ADJOURN

APPENDIX B
Plenary Presentations

APPENDIX C
Breakout Group Summary Presentations

APPENDIX D –
Strategic Directions for Hydrogen Delivery Workshop
LIST OF PARTICIPANTS

Belinda Aber
5901 South Rice
Bellaire, TX 77401
Phone: (713) 432-6659
Fax: (713) 432-2002
Email: aberb@chevrontexaco.com

Mark Ackiewicz
TMS, Incorporated
Phone:
Fax:
Email: mackiewicz@tms-hq.com

John Anderson
Senior Associate
TMS
955 L'Enfant Plaza North, S.W.
Suite 1500
Washington, DC 20024
Phone: (202) 554-4616
Fax: (202) 554-4676
Email: janderson@tms-hq.com

Raymond Anderson
Hydrogen Initiative Leader
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625
Mail Stop 2110
Idaho Falls, ID 83415-2110
Phone: (208) 526-1623
Fax: (208) 526-9822
Email: anderp@inel.gov

Rodney Anderson
Product Manager
U.S. Department of Energy/NETL
P.O. Box 880
Morgantown, WV 26507
Phone: (304) 285-4709
Fax: (304) 285-4216
Email: rodney.anderson@netl.doe.gov

Greg Baehr
Project Manager
Praxair, Incorporated
222 Pennbright Drive
Houston, TX 77090
Phone: (281) 872-2138
Fax: (281) 872-2202
Email: greg_baehr@Praxair.com

Roger Ballentine
President
Green Strategies
1312 18th Street, N.W.
Washington, DC 20036
Phone: (202) 293-1123
Fax: (202) 293-1124
Email: roger@greenstrategies.com

Gene Berry
7000 East Avenue L-644
Livermore, CA 94550
Phone: (925) 424-3621
Fax: (925) 423-7914
Email: berry6@llnl.gov

Ross Brindle
Energetics, Incorporated
7164 Gateway Drive
Columbia, MD 21046
Phone: (410) 953-6239
Fax: (410) 290-0377
Email: rbrindle@energetics.com

Jim Campbell
Manager, Pipeline Engineering
Air Liquide Process and ConStreet
2700 Post Oak Boulevard
Suite 1800
Houston, TX 77056
Phone: (713) 499-6075
Fax: (713) 624-8898
Email: jim.campbell@airliquide.com

Stephen Chalupa
Fuels Supply Manager
ChevronTexaco Technology Ventures
3901 Briarpark
Houston, TX 77042
Phone: (713) 954-6978
Fax: (713) 954-6979
Email: chalusn@chevrontexaco.com

Ron Chittim
American Petroleum Institute
1220 L Street, N.W.
Washington, DC 20005
Phone: (202) 682-8176
Fax: (202) 682-8051
Email: chittim@api.org

Max Clausen
Program Manager
Pacific Northwest National Laboratory
P.O. Box 1970
Richland, WA 99352
Phone: (301) 442-8828
Email: max.clausen@pnl.gov

Steven Cohen
Business Development Manager
Teledyne Energy Systems, Incorporated
10707 Gilroy Road
Hunt Valley, MD 21031-1311
Phone: (410) 891-2297
Fax: (410) 771-8619
Email: steve.cohen@teledynees.com

Terry Copeland
Vice President, Product Development
Millennium Cell, Incorporated
1 Industrial Way West
Eatontown, NJ 7724
Phone: (732) 542-4000
Fax: (732) 542-4010
Email: copeland@millenniumcell.com

Anthony Cugini
Focus Leader
U.S. Department of Energy/NETL
626 Cochrans Mill Road
Pittsburgh, PA 15236
Phone: (412) 386-6023
Fax: (412) 386-5920
Email: anthony.cugini@netl.doe.gov

Genevieve Cullen
Senior Vice President
Green Strategies
1312 18th Street
Second Floor
Washington, DC 20036
Phone: (202) 293-1123
Fax: (202) 293-1124
Email: gen@greenstrategies.com

Maria Curry-Nkansah
Business Development Manager
BP
150 West Warrenville Road
Mail Code J-7
Naperville, IL 60563-8460
Phone: (630) 420-5832
Fax: (630) 420-4831
Email: curry-me@bp.com

Peter Devlin
Lead Management and Program Analyst
U.S. Department of Energy
1000 Independence Avenue, S.W.
Forrestal Building, EE-2H
Washington, DC 20585
Phone: (202) 586-4905
Fax: (202) 586-9811
Email: peter.devlin@ee.doe.gov

Raymond Drnevich
Manager, Hydrogen Technology
Praxair, Incorporated
175 East Park Drive
Tonawanda, NY 14150
Phone: (716) 879-2595
Fax: (716) 879-7091
Email: ray_drnevich@praxair.com

Rod Dyck
Associate Director
National Transportation Safety Board
490 L'Enfant Plaza East, S.W.
Washington, DC 20594
Phone: (202) 314-6469
Fax: (202) 314-6482
Email: dyckr@ntsb.gov

Steve Folga
Systems Engineer
Argonne National Laboratory
9700 South Cass Avenue
Building 900, Room M05
Argonne, IL 60439
Phone: (630) 252-3728
Fax: (630) 252-6500
Email: sfolga@anl.gov

Charles Forsberg
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831-6179
Phone: (865) 574-6783
Fax: (865) 574-9512
Email: forsbergcw@ornl.gov

Christopher Freitas
Program Manager
Office of Fossil Energy
U.S. Department of Energy, FE-32
1000 Independence Avenue, S.W.
Forrestal Building, Room 3E-028
Washington, DC 20585
Phone: (202) 586-1657
Fax: (202) 586-6221
Email: christopher.freitas@hq.doe.gov

David Greene
Corporate Research Fellow
National Transportation Research Center
Oak Ridge National Laboratory
2360 Cherahala Boulevard
Knoxville, TN 37932
Phone: (865) 946-1310
Fax: (865) 946-1314
Email: dlgreene@ornl.gov

Esin Gulari
Acting Assistant Director, Engineering
National Science Foundation
4201 Wilson Boulevard
Suite 525
Arlington, VA 22230
Phone: (703) 292-8300
Fax: (703) 292-9013
Email: egulari@nsf.gov

Donald Hardesty
Deputy Director
Sandia National Laboratories
7011 East Avenue
MS9054
Livermore, CA 94550
Phone: (925) 294-2321
Fax: (925) 294-2276
Email: drharde@sandia.gov

J. Stephen Herring
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625, MS 3860
Idaho Falls, ID 83415-3860
Phone: (208) 526-9497
Fax: (208) 526-2930
Email: sth@inel.gov

Keith Jamison
Engineer
Energetics, Incorporated
7164 Gateway Drive
Columbia, MD 21046
Phone: (410) 953-6201
Fax: (410) 290-0377
Email: kjamison@energetics.com

Karl Jonietz
Los Alamos National Laboratory
MS D429
Los Alamos, NM 87545
Phone: (505) 667-1311
Fax: (505) 665-4292
Email: kjonietz@lanl.gov

Jay Keller
Hydrogen Program Manager
Sandia National Laboratories
P.O. Box, MS 9053
Livermore, CA 94551-0969
Phone: (925) 294-3316
Fax: (925) 294-1004
Email: jokelle@sandia.gov

Moe Khaleel
Laboratory Fellow
Pacific Northwest National Laboratory
P.O. Box 999
Richland, WA 99352
Phone: (509) 375-2438
Fax: (509) 375-6605
Email: moe.khaleel@pnl.gov

Marty Krongold
Business Manager
Air Liquide America L.P.
200 Chastain Center Boulevard
Suite 295
Kennesaw, GA 30144
Phone: (678) 354-8219
Fax: (678) 354-8219
Email: marty.krongold@airliquide.com

Carl Landahl
Argonne National Laboratory
9700 South Cass Avenue
Building 362
Argonne, IL 60439-4815
Phone: (630) 252-1762
Fax: (630) 252-9281
Email: clandahl@anl.gov

Stephen Lasher
TIAX
15 Acorn Park
Cambridge, MA 2140
Phone: (617) 498-6108
Fax: (617) 498-7054
Email: lasher.stephen@tiax.biz

William Liss
Associate Director
Gas Technology Institute
1700 South Mount Prospect Road
Des Plaines, IL 60018
Phone: (847) 768-0753
Fax: (847) 768-0501
Email: william.liss@gastechnology.org

Michael Manning
Development Associate
Praxair, Incorporated
175 East Park Drive
Tonawanda, NY 14151
Phone: (716) 879-2987
Fax: (716) 879-7030
Email: mike_manning@praxair.com

Michael McGowan
Marketing Manager, Hydrogen Energy
BOC Gases
575 Mountain Avenue
Murray Hill, NJ 7974
Phone: (908) 771-1086
Fax: (908) 771-1903
Email: michael.mcgowan@us.gases.boc.com

Gilbert McGurl
U.S. Department of Energy
P.O. Box 10940
Pittsburgh, PA 15236-0940
Phone: (412) 386-4462
Fax: (412) 386-4561
Email: mcgurl@netl.doe.gov

Shawna McQueen
Energetics, Incorporated
7164 Gateway Drive
Columbia, MD 21046
Phone: (410) 290-0370 x235
Fax: (410) 290-0377
Email: smcqueen@energetics.com

James Merritt
Research and Development Program Manager
U.S. Department of Transportation
RSPA/OPS
793 Countrybriar Lane
Denver, CO 80129
Phone: (303) 683-3117
Fax: (303) 346-9192
Email: james.merritt@rspa.dot.gov

Marianne Mintz
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (630) 252-5627
Fax: (630) 252-3443
Email: mmintz@anl.gov

Trent Molter
Senior Vice President
Proton Energy Systems, Incorporated
10 Technology Drive
Wallingford, CT 6492
Phone: (203) 678-2185
Fax: (203) 949-8078
Email: trent.molter@protonenergy.com

Theodore Motyka
Manager, Hydrogen Technology
Westinghouse Savannah River Site
Building 773-41A, 144
Aiken, SC 29808
Phone: (803) 725-0772
Fax: (803) 725-4553
Email: ted.motyka@srs.gov

George Parks
Research Associate
ConocoPhillips
356 PL BTC
Bartlesville, OK 74004
Phone: (918) 661-7780
Fax: (918) 662-1097
Email: george.d.parks@conocophillips.com

Mark Paster
General Engineer
U.S. Department of Energy
1000 Independence Avenue, S.W.
Forrestal Building, EE-2H
Washington, DC 20585
Phone: (202) 586-2821
Email: mark.paster@hq.doe.gov

John Petrovic
Laboratory Fellow
Los Alamos National Laboratory
U.S. Department of Energy
Forrestal Building, EE-2H
1000 Independence Avenue, S.W.
Washington, DC 20585
Phone: (202) 586-8058
Email: john.petrovic@ee.doe.gov

Guido Pez
Chief Scientist
Air Products and Chemicals, Incorporated
7201 Hamilton Boulevard
Allentown, PA 18195-1501
Phone: (610) 481-4271
Fax: (610) 481 7719
Email: pezgp@apci.com

Elizabeth Pfeiffer
Environmental Compliance Manager
BMW of North America
1 BMW Plaza
Montvale, NJ 7645
Phone: (201) 573-2194
Fax: (201) 782-0764
Email: elizabeth.pfeiffer@bmwna.com

James Ragland
Director, ERG
Aramco Services Company
1667 K Street, N.W.
Suite 1200
Washington, DC 20006
Phone: (202) 223-7750
Fax: (202) 223-7756
Email: jim.ragland@aramcoservices.com

Venki Raman
Project Director
Air Products and Chemicals, Incorporated
7201 Hamilton Boulevard
Allentown, PA 18195
Phone: (610) 481-8336
Email: ramansv@apci.com

Rich Scheer
Vice President
Energetics, Incorporated
901 D Street
Suite 100
Washington, DC 20024
Phone: (202) 479-2748
Fax: (202) 479-0229
Email: rscheer@energeticsincorporated.com

Matthew Ringer
Chemical Engineer/Analyst
National Renewable Energy Laboratory
1617 Cole Boulevard
MS 1613
Golden, CO 80401
Phone: (303) 275-3703
Fax: (303) 275-2905
Email: matthew_ringer@nrel.gov

Gerry Runte
Gas Technology Institute
1700 South Mount Prospect
Des Plaines, IL 60018
Phone: (847) 768-0730
Email: gerry.runte@gastechnology.org

Scott Savage
Manager, Zone Production
Air Liquide America L.P.
2700 Post Oak Boulevard
Suite 1800
Houston, TX 77056
Phone: (713) 624-8265
Fax: (713) 624-8262
Email: scott.savage@airliquide.com

Edward Schmetz
Portfolio Manager
U.S. Department of Energy
19901 Germantown Road
Germantown, MD 20874
Phone: (301) 977-3581
Fax: (301) 903-2238
Email: edward.schmetz@hq.doe.gov

Paul Scott
ISE Research
7345 Mission Gorge Road
San Diego, CA 92120
Phone: (619) 287-8785, Ext. 140
Email: pscott@isecorp.com

Prentiss Searles
American Petroleum Institute
1220 L Street
Washington, DC 20005
Phone: (202) 682-8227
Fax: (202) 682-8051
Email: searlesp@api.org

Marvin Singer
Senior Advisor, Applied Energy Programs
Office of Science
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585
Phone: (202) 586-4336
Fax: (202) 586-8054
Email: marvin.singer@science.doe.gov

Brad Smith
Project Manager
Shell Hydrogen
777 Walker Street
TSP-2110
Houston, TX 77002
Phone: (713) 241-3239
Fax: (713) 241-3240
Email: brad.smith@shell.com

Richard Smith
Program Director
National Science Foundation
4201 Wilson Boulevard
Room 525
Arlington, VA 22230
Phone: (703) 292-8371
Fax: (703) 292-9054
Email: rnsmith@nsf.gov

Allen Spivey
Manager
Mechanical Engineering and Field Operations
Distribution Operations Technology
Gas Technology Institute
1700 South Mount Prospect Road
Des Plaines, IL 60018-1804
Phone: (847) 768-0867
Fax: (847) 768-0569
Email: allen.spivey@gastechnology.org

Peter Teagan
TIAX
15 Acorn Park
Cambridge, MA 2140
Phone: (617) 498-6054
Fax: (617) 498-7054
Email: teagan.w@tiax.biz

Steve Thomas
Manager, Computational Science
Sandia National Laboratories
P.O. Box 969
Livermore, CA 94551-0969
Phone: (925) 294-2954
Fax: (925) 294 1200
Email: swthoma@sandia.gov

Michele Touvelle
Planning Advisor
ExxonMobil
3225 Gallows Road
Fairfax, VA 22037
Phone: (703) 846-7179
Fax: (703) 846-6181
Email: michele.s.touvelle@exxonmobil.com

Brian Turk
Research Chemical Engineer
RTI
3040 Cornwallis Road
P.O. Box 12194
Research Triangle Park, NC 27709-2194
Phone: (919) 541-8024
Fax: (919) 541-8000
Email: bst@rti.org

Lixin You
Senior Scientist/Engineer
ChevronTexaco
100 Cummings Park
Woburn, MA 1801
Phone: (781) 932-8080, Ext. 132
Fax: (781) 932-8181
Email: lixin.you@analyticenergy.com